

Numerical and Experimental Investigation of the Piezoelectric Flapping Wing Micro-Air-Vehicles Propulsion

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ABSTRACT

The flapping flight is advantageous for its superior maneuverability and much more aerodynamically efficiency for the small size UAV when compared to the conventional steady-state aerodynamics solution. Especially, it is appropriate for the Micro-air-vehicle (MAV) propulsion system, where the flapping wings can generate the required thrust. This paper investigated such solution, based on the piezoelectric patches, which are attached to the flexible plates, in combination with an appropriate amplification mechanisms. The numerical and experimental flow analyses have been carried out for the piezoelectric flapping plate, in order to characterize the fluid structure interaction induced by the swinging movement of the oscillating plate. The time-resolved Particle Image Velocimetry (PIV) measurements were conducted on a piezoelectric flapping wing with finite span operating at 84.8 Hz in air in order to validate the numerical simulations, and the comparison showed good matching, as reported in this paper.

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INTRODUCTION

The rapid progress in all facets of fluid mechanics research has made it essential that the research activities are conducted in close cooperation between experimentalists, numerical analysts and theoreticians. In the early stages of the Computational Fluid Dynamics (CFD) development the improvements of the numerical simulation process were so rapid that it was expected that CFD would eliminate the role of Experimental Fluid Dynamics (EFD) all together. However, experience showed that in order to get insight in complex physics phenomena, the experiments are still the most appropriate and trustable approach to follow. It is very well accepted that the CFD codes, ones validated against the experimental data, become an effective tool for the production of a comprehensive flow database, representing an important knowledge base, which can significantly reduce the need for large and costly experiments. The strengths of various tools in EFD and CFD should be used judiciously, and compensate each other drawbacks, in order to extract the most relevant quantities to solve the engineering problem, as shown in [Figure 1](#) [1], and applied in this work.

The recent advances of small CCD cameras, as infrared sensors, have led to significant interest in the small flying vehicles development, called Micro Air Vehicles (MAVs), which can be considered as a highly portable platform for the tiny cameras and similar size sensors. It is demonstrated in

nature, by birds and insects, that the flapping flight, and thus the flapping wing MAV propulsion can be advantageous, as it is characterized by its greater maneuverability and lifting capability, experienced at the low flight speeds, which are especially important when considering the indoor environments. The small flapping wing MAVs would not only move like insects, but considering its typical dimensions, it flies almost unnoticed in only the millimeter range air space. The aerodynamic mechanisms of the insect flight, which allows the high lift forces and maneuverability is highly complex. The MAVs fly, due to their small dimensions and low speed at extremely low Reynolds number (100,000 or below), when compared to the conventional aircrafts. A vital challenge, in the creation of the bird/insect-mimicking flapping machine, is to select an actuator, which could produce sufficient wing deflections to enable the required flight aerodynamics performance.

PIEZOELECTRIC FLAPPING PLATES

The propulsion mechanisms is an important limitation of MAV development. Currently, the most recent MAVs are constructed with the electric-powered systems, which efficiently convert the stored energy into usable energy, but coming with the inherent drawback that the present battery equipment has a low energy density storage. It is well known

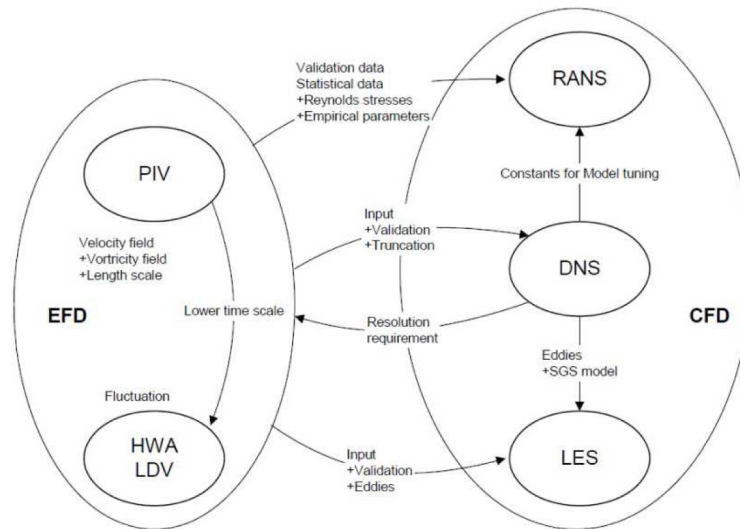


Figure 1. Use of EFD and CFD tools.

that Gasoline has a very high energy density storage, but it is also true that the combustion engines are very inefficient at the MAVs scale, and in addition produce a lot of noise. The limitation of the existing propulsion systems, which are available for MAVs, is the short flight endurance, which comes to less than 10 minutes of flight in many cases. The MAV endurance is limited mainly by the efficiency of the energy storage and propulsion. The rotary-wing MAVs are especially limited in endurance, as they consume great amounts of power in order to fly. For the mentioned reasons, the researchers have begun to investigate the rotary and flapping-wing MAV designs that could operate at low speeds and offer the possibility to hover, as alternative to the fixed wings solution, which is inappropriate for the MAVs use within indoor and limited space, thus within complex aerodynamic environments. For the miniature scale of MAVs, the flapping wing vehicles could be the favored approach to follow, because of their existence in the nature (birds, insects), and their capability to harness the low Reynolds number unsteady vortex lift effects. That's why researchers are trying to mimic the wing motions of birds and insects to build flapping wing, as an adequate MAV's propulsion system.

Up till now, weight and mechanical system complexity are frequently experienced using these mechanisms, and one of the most important constraints to the development of the flapping wing MAV is the lack of a compact, high energy density propulsion mechanism. This is a great challenge, since at small MAV scales the mechanical components (bearings, conventional joints, etc) are too heavy and give inefficient actuation, and in addition require a complex control system.

In this paper, a piezoelectric fan is analyzed to be considered as the flapping wing mechanism. It is fabricated by bonding a piezoelectric patch, or several patches, to a passive elastic plate. The flapping motion is produced when

the two-patches are activated in such way that when one expands, the other contracts. The activation is induced by an alternating voltage, with a frequency equal to the first resonance frequency of the piezoelectric fan structure. Once this happens, the blade bonded to the piezoelectric patch flaps back and forth as shown in [Figure 2](#).

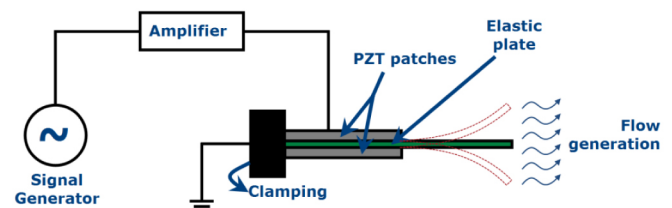


Figure 2. Basic working principle of a piezoelectric flapping plate.

The flapping wing systems are inspired by the insect flight, and usually involve the wing undertaking pitching, yawing and sweeping motion within one flapping cycle. Various mechanisms of such motor-driven actuators model have been developed to imitate this difficult flapping motion. Piezoelectric ceramics offer the possibility for a flapping wing propulsion system with integrated electronics and simplified control systems. The piezoelectric actuators are also light weight and easy to integrate into the MAV platform. Some kind of motion amplification mechanism is required to achieve large displacements with these actuators.

Piezoelectric actuated four-bar mechanisms for micromechanical flying insect thorax were developed in [2]. A system with one piezoelectric unimorph actuator and three flexural-based mechanisms to transform the linear output of the actuator into single-degree-of freedom flapping motion was developed to imitate the flapping flight [3]. A four-bar linkage system driven by lightweight piezo-composite actuator was developed in [4] to mimicking the flapping wing

system of insects. The University of California has done considerable work on a piezoelectric actuated flapping wing MAV and used a pair of piezoelectric unimorph actuators and four bar mechanisms [5]. The four-bar mechanism had two flexible links. PZT-5H and PZN-PT based unimorph actuators were utilized at the input link of the four-bar. The kinematics and dynamics behavior of the proposed wing structure, with two parallel four-bar mechanisms were analyzed, and DC forces generated at the wing were computed for checking the feasibility of the design. They constructed a four-bar prototype using laser micro machining and folding techniques.

In comparison with the four-bar and other mechanism, the simplest motion amplification system is using a piezo fan at resonance [6]. The motion pattern of an insect flapping is quite complex as mentioned earlier and has three DOF's. To realize those three DOF, multiple piezo fans need to be used, since one piezo fan can only produce one DOF motion. By using two piezo fans in parallel, connected to a wing structure, creates the ability to provide flapping and rotation motion, by controlling the phase of the actuator input and the amplitude difference between the two piezo fans.

Therefore, to obtain a complex wing motions, the control system has to be designed to drive multi piezo actuators with signals of different amplitudes and phases. In addition, such approach allows the tuning and control of the phase between the flapping and rotational motion, which represents a key for flapping flight control. Today, commercial piezo fans are used to build flapping wing prototypes for MAV-s, with two degrees of freedom (DOF) motion.

By controlling the phase difference between the input voltages of two piezoelectric fans, the wing rotation motion can be controlled. The wing will be flapping when the two fans are in-phase. To obtain the complex wing motion, it should be possible to drive multi piezoelectric actuators with signals of different amplitudes and phases. This design will also enable the adjustment and control of the phase between the flapping and twisting motions which is a key for flapping flight control.

Another working principle is placing the piezoelectric flapping wings on a steady wing of a MAV (Figure 3), thus replacing conventional propulsion system in fixed wing MAV with a flapping wing propulsion system. If enough thrust can be generated using these flapping wing structures, the MAV would be able to sustain the flight. However, the integration of the propulsion system in the fixed wing MAV is expected to be, not easy to construct.

It can be concluded that a piezoelectric flapping wing construction, based on piezo fans, show potential to be used as a flapping wing for MAV. The total power consumption must be lower or equal to the existing MAV systems that are driven by other propulsion systems like propellers. To be effective, the piezo fan created thrust needs to be in the same range of the one created by propeller. Basically, the available commercial piezo fans do not have enough tip deflection and surface area to generate an appropriate thrust. Therefore, a

wing construction is fabricated and used. This wing prolongs the piezo fan with two stiff spars - skin connected, to generate the air displacement.

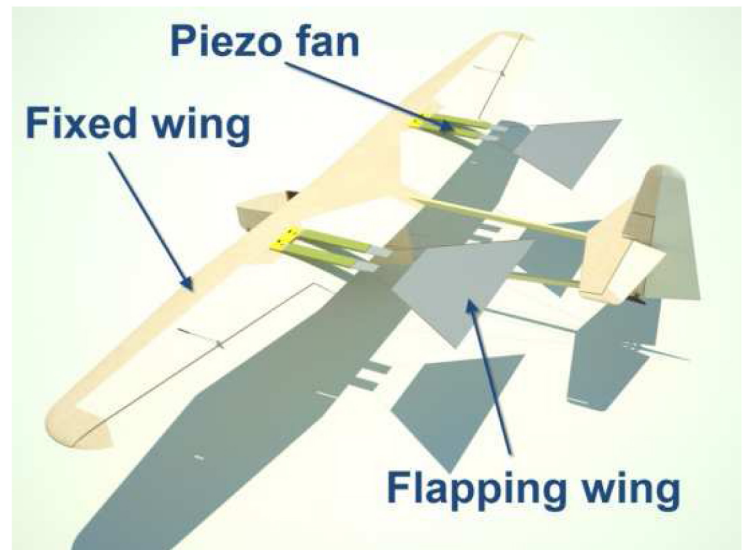


Figure 3. Piezoelectric flapping wing propulsion system.

The primary objective of this paper is to present the results from the conducted numerical simulations and experimental measurements of the flow generated by the piezoelectric fans. In order to achieve such objective, it was important to develop a fluid-structure interaction model of the flow induced by the piezoelectric flapping wings, and to further validate the operational principles of these wings models, by experimentally visualizing the fluid-structure interaction phenomena.

COMPUTATIONAL ANALYSIS

For the numerical simulations the commercially available computational fluid dynamics software package ANSYS CFX is used. The Large Eddy Simulation (LES) model was used as turbulence model for the unsteady flow. The flow is dominated by large-scale vortices shaded from the oscillating body. There is a strong interaction between the vortices, which let them break apart, and provide intensive mixing, which is not produced by any turbulence models in Reynolds-averaged Navier-Stokes equations (RANS). It is generally known that RANS models fail to predict such complex flows, within a proper accuracy. Thus, it is important to apply some of the vortex resolving turbulence models, like Direct Numerical Simulation (DNS), LES or a RANS-LES hybrid one.

The oscillations are forced by a prescribed harmonic motion, computed from the Laser Doppler Vibrometry (LDV) measurements. Both 2D and 3D simulations were conducted for this test case. The computational grid for the 2D and 3D case consisted of 1.5 and 15 million elements, respectively. To be able to compare the computational and experimental results for the 3D case, different 2D planes in the